

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

*Technical Report 32-1553*

*Fault Determinations in Electroexplosive Devices  
by Nondestructive Techniques*

*Vincent J. Menichelli*

*Louis A. Rosenthal*

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JET PROPULSION LABORATORY  
CALIFORNIA INSTITUTE OF TECHNOLOGY  
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National Aeronautics and Space Administration**

## **Preface**

The work described in this report was performed by the Propulsion Division of the Jet Propulsion Laboratory. Louis A. Rosenthal, a consultant to the Jet Propulsion Laboratory, is a professor in the Department of Electrical Engineering, Rutgers University, New Brunswick, New Jersey.

## **Acknowledgment**

The authors would like to acknowledge the assistance of H. Jeffries in preparing electroexplosive devices for testing and in conducting the experiments.

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## **Abstract**

Several nondestructive test techniques have been developed for electroexplosive devices. The bridgewire responds, when pulsed with a safe level current, by generating a characteristic heating curve. The response is indicative of the electro-thermal behavior of the bridgewire-explosive interface. Bridgewires which deviate from the characteristic heating curve have been dissected and examined to determine the cause of the abnormality. Deliberate faults have been fabricated into squibs. The relationship of the specific abnormality and the fault associated with it is demonstrated.

# Fault Determinations in Electroexplosive Devices by Nondestructive Techniques

## I. Introduction

The evaluation of the reliability, quality, and behavior of an electroexplosive device (EED) is a formidable problem. Statistical methods, which require destruction of the EED, have been applied with some success. For example, predictions can be made as to the number and type of failure which can be expected to occur within a given lot of EEDs. However, these methods do not predict the specific unit that will fail or the failure mode.

Although statistical methods are acceptable for some applications, they practically do not meet the high reliability needs of the space industry. Special requirements of the space industry necessitate more detailed knowledge of the quality of each EED to be used. Failure of an EED during a space mission can result in partial or complete loss of the mission and perhaps loss of human life. Some space missions (i.e., Mars exploration) can last from 6 months to a year. Future space missions can be expected to last as long as 10 years, during which time EEDs will be called upon to function. To demonstrate by statistical methods the high reliability needed of EEDs for these types of space missions would require the firing of large quantities of EEDs. Despite the predicted reliability value obtained, some doubt about the particular EEDs used will always remain.

This report describes nondestructive techniques which yield data as to the quality and normal behavior of each EED without firing or degrading the unit. These techniques are limited to the bridgewire/explosive/header interface (Fig. 1), which is considered a critical link in the electroexplosive chain. Evaluation of this interface will contribute valuable information on unit performance. The quality of the EED beyond this interface can be evaluated to a certain degree by techniques such as weighing, X-ray, and neutron radiography.

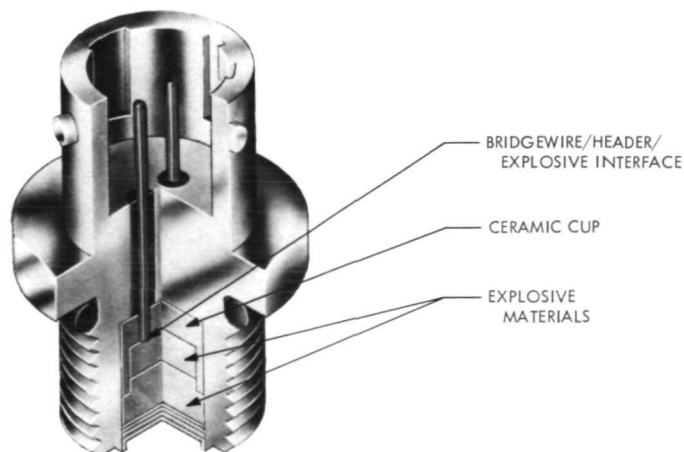


Fig. 1. Typical aerospace electroexplosive device



## II. Instrumentation and Technique

The nondestructive techniques are based on introducing a current waveform into the bridgewire. The current pulse is small enough to avoid firing or degradation of the EED, yet large enough to provide a meaningful electrothermal response observed as a voltage developed at the bridgewire terminals. The bridgewire must have some temperature coefficient of resistivity and the signal developed can be related to the bridgewire temperature rise. Variations in the signal developed from unit to unit can be related but not limited to the following areas:

- (1) Bridgewire—resistance behavior responding to wire imperfections, i.e., current crowding.
- (2) Welds—poor welds producing certain nonohmic nonlinearities.
- (3) Thermal transfer—intimacy of contact between bridgewire, header, and explosive mix.
- (4) Strain behavior of bridgewire—movement of the bridgewire upon heating, resulting from the coefficient of expansion.

Two types of apparatus have been used to observe the electrothermal response at the bridgewire terminals. Instrumentation devices for what is referred to as "transient pulse testing" and "electrothermal follow display" are used to perform the tests in a rapid and efficient manner. For each instrument, the bridgewire becomes one arm of a Wheatstone Bridge.

The transient pulse apparatus (Ref. 1) applies a step current waveform (approximately 50 ms on and then off) to the Wheatstone bridge circuit. As the bridgewire heats, the Wheatstone bridge unbalances, and an error voltage is developed across the bridgewire terminals. Additional features of the instrumentation allow a measurement of the thermal conductance, the thermal time constant, and the cold resistance of the bridgewire. A lumped model analysis of the bridgewire system is the basis for derivation of the electrothermal equations (Ref. 2). The apparatus furnishes quantitative results and provides for a visual oscilloscope display of the error voltage which can be related to the temperature rise in the bridgewire. Figure 2 shows a typical heating curve obtained from a normal, healthy EED; H represents the horizontal display and V, the vertical display.

The second apparatus, for electrothermal follow display (Ref. 3), employs a steady-state, 10-Hz, sinusoidal current to the Wheatstone bridge circuit. A self-balancing fea-

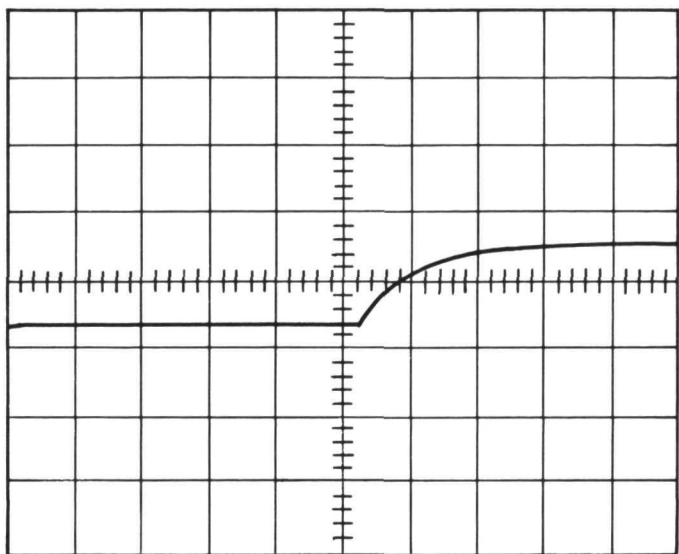
ture of the Wheatstone bridge takes the EED through a thermal cycle. The temperature excursion can be controlled and the bridgewire signal displayed on an oscilloscope. The display shows how bridgewire heating unbalances the Wheatstone bridge in a cyclic manner, producing a Lissajous display (Ref. 4). This test is qualitative and is best applied as a gross inspection tool. Figure 3 shows a typical Lissajous response obtained from a normal, healthy EED.

## III. Observed Traces

Approximately 1,000 bridgewires, in a variety of EED designs, have been examined with the transient pulse and electrothermal follow apparatus. Various abnormal responses have been observed. Figure 4 shows several abnormal heating curves resulting from the transient pulse test. Three types were selected to demonstrate different fault mechanisms. All thermally induced nonlinearities require a time delay and never appear as trace discontinuities. Nonohmic nonlinearities occur instantaneously and will generally appear at the start of the heating curve. Figure 4a is typical of a nonohmic, nonlinear response attributed to defects in the bridgewire-to-pin weld. Figure 4b starts with a normal exponential rise, but after the bridgewire reaches its peak temperature, something happens to cool it. This phenomenon is related to a phase change taking place in the explosive mixture. Figure 4c, at the onset, shows a nonohmic nonlinear response and then, later in time, thermally induced nonlinearities. The nonohmic response demonstrates weld defects, while the thermal nonlinearities suggest poor thermal contact between the bridgewire and explosive mix. In all cases where an abnormal heating curve was observed with the transient pulse test, a corresponding abnormal Lissajous response was observed with the electrothermal follow test. Figure 5 compares a normal electrothermal follow display response from a healthy EED with a response from a defective EED. Identification of some faults or defects associated with a particular abnormal transient pulse response has been made. These have been verified through case histories and by purposely fabricating EEDs with known defects and observing the electrothermal response.

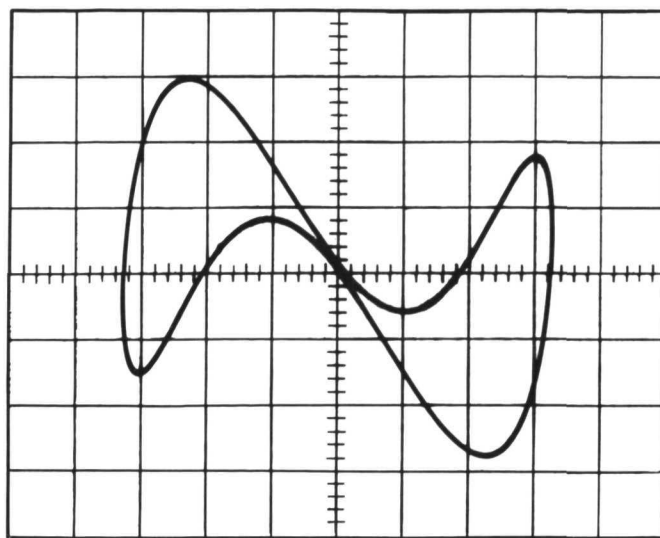
## IV. Investigation and Discussion of Abnormal Responses

The responses observed with the transient pulse and electrothermal follow tests are directly related to the



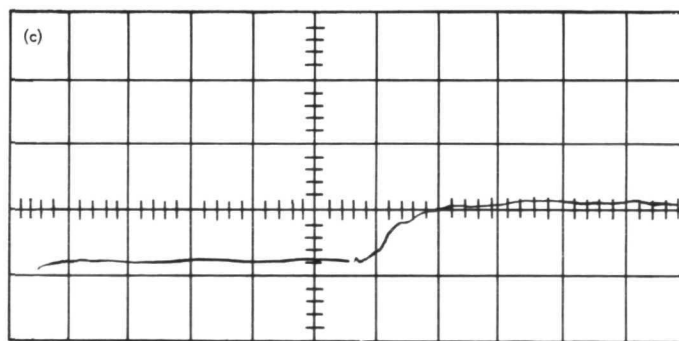
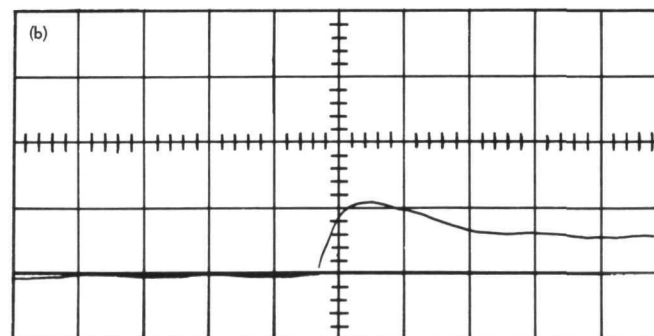
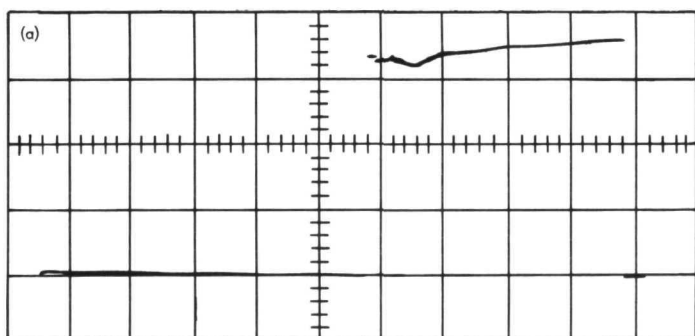
V = 5 mV/div  
H = 10 ms/div

**Fig. 2. Typical heating curve response from a healthy, normal EED as sensed by the voltage drop at the bridge-wire**



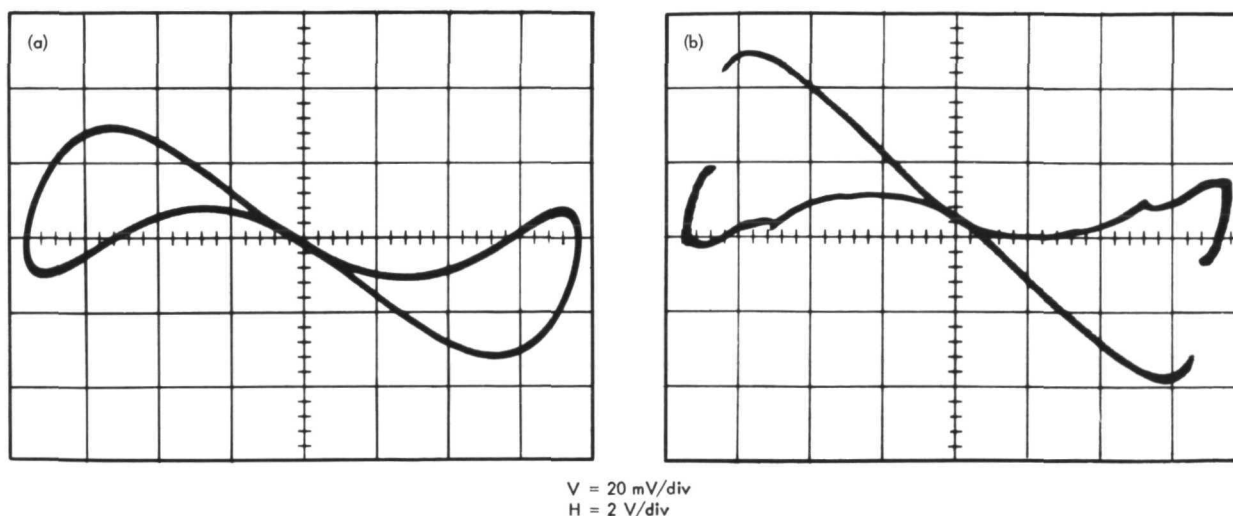
V = 50 mV/div  
H = 2 V/div

**Fig. 3. Typical Lissajous response from a healthy, normal EED; H is proportional to drive current, V is proportional to bridgewire error voltage**



V = 5 mV/div  
H = 10 ms/div

**Fig. 4. Several abnormal, suspicious heating curves as a result of defects in the EEDs**



**Fig. 5. Comparison of a normal thermal follow response from a healthy EED (a) with a response from a defective EED (b)**

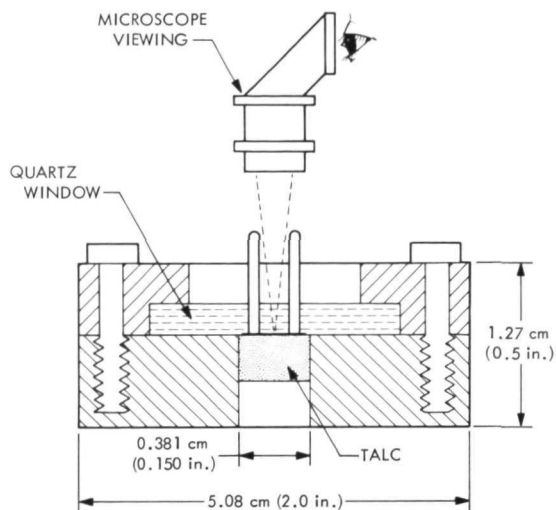
condition of the bridgewire, bridgewire weld, and header/bridgewire/explosive interface. To visually observe this interface, a test fixture with a quartz header (Fig. 6) was designed. Microscopic observations were made while the bridgewire was subjected to the transient pulse test. Figure 7 is a photomicrograph (double exposure) of the bridgewire heating cycle in air. As the bridgewire heats, the wire expands and buckles. This action strains the wire at the weld joints.

Other observations were made with talc loaded on the bridgewire at  $34.5 \times 10^6 \text{ N/m}^2$  (5 kpsi) and  $68.9 \times 10^6 \text{ N/m}^2$  (10 kpsi). Figure 8 shows the bridgewire before and after pulsing at each pressure. At  $34.5 \times 10^6 \text{ N/m}^2$  loading pressure, some of the talc became lodged between the bridgewire and the header. When the wire is pulsed repeatedly, the talc density is low enough to allow the bridgewire to buckle and move the powder away in the manner of a tunneling effect. At  $68.9 \times 10^6 \text{ N/m}^2$ , the tunneling effect is not apparent. These tests pointed out the importance of correct loading pressure to ensure that the explosive material is always in intimate contact with the bridgewire. The tunneling effect observed was a result of the transient pulse applied to the bridgewire; however, one can conceive of a similar effect resulting from external temperature cycling or vibration.

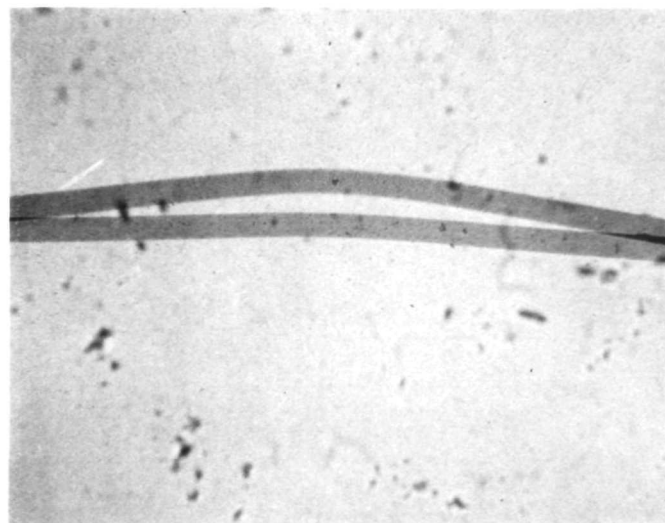
An air gap between the bridgewire and explosive material, which can be determined by the transient pulse test, is demonstrated in Fig. 9. Here we see a rapid rise in the heating curve, since the bridgewire is not in inti-

mate contact with the explosive material and the heat loss is small. As the bridgewire expands and buckles, it makes contact with the explosive, and the rate of temperature rise of the bridgewire decreases, creating a knee in the curve. This condition can lead to decreased reliability because of possible bridgewire burnout before the bridgewire contacts the explosive. As the loading pressure of the explosive is increased, the ability of the bridgewire to buckle when heated is minimized. However, the strain in the wire remains, although it is now applied along the axis of the bridgewire, terminating at the weld joints. Thus the confined bridgewire is under considerable strain. If a poor or defective weld exists, a nonohmic, nonlinear response will result and will be observed when the bridgewire is tested by the transient pulse or electrothermal follow technique.

Verification that poor welds lead to nonohmic nonlinear responses was made by actually building a bridgewire systems purposely containing bad welds and also by dissecting EEDs which demonstrated nonohmic nonlinear responses. Figure 10 shows two purposely fabricated bad bridgewire welds and the resulting heating curves observed by the transient pulse and thermal follow techniques. Actual EEDs displaying nonohmic nonlinear responses were dissected and the explosive carefully removed from the bridgewire header surface, exposing the welds. Figure 11 reveals the welds found in two cases. In the left picture, corrosion has been at work, while in the right picture, the weld was improperly made and the bridgewire appears to be poorly fused to the pin.

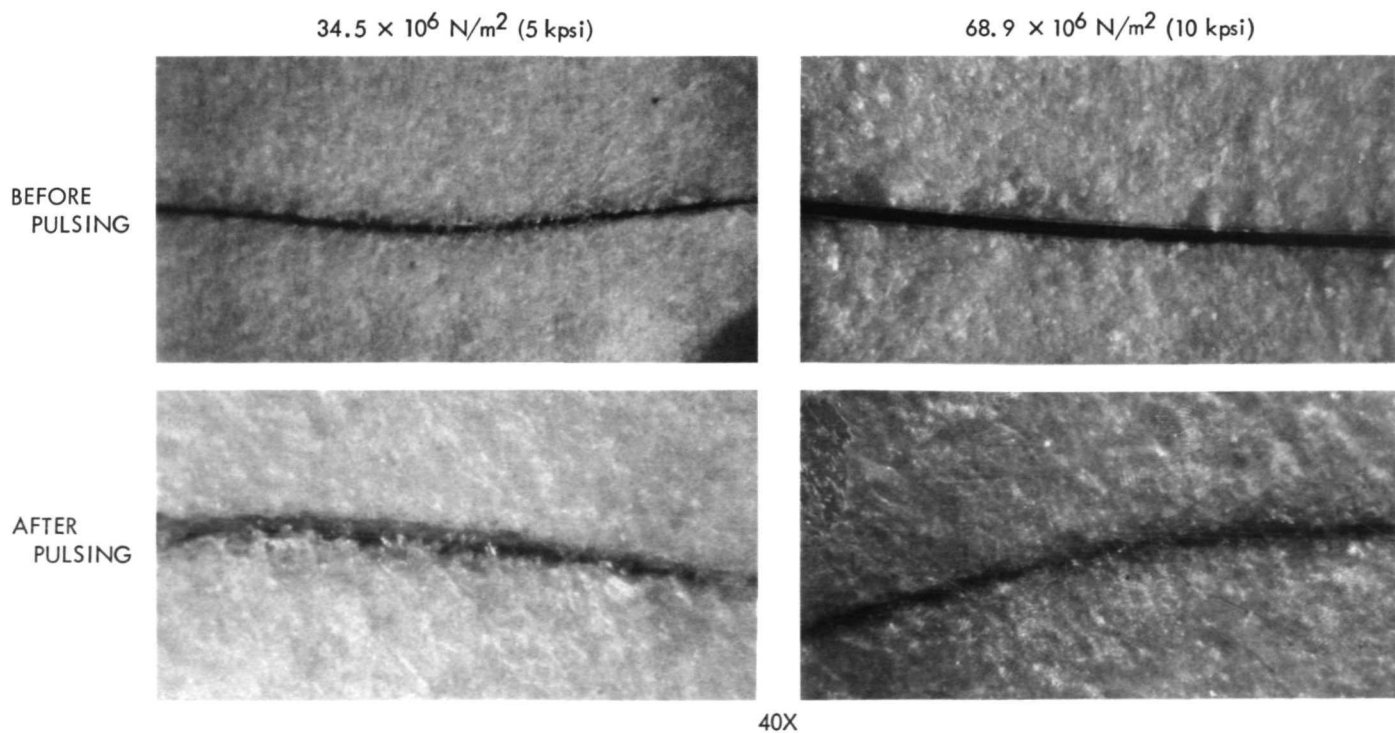


**Fig. 6. Test fixture used to observe bridgewire behavior subjected to transient pulse**

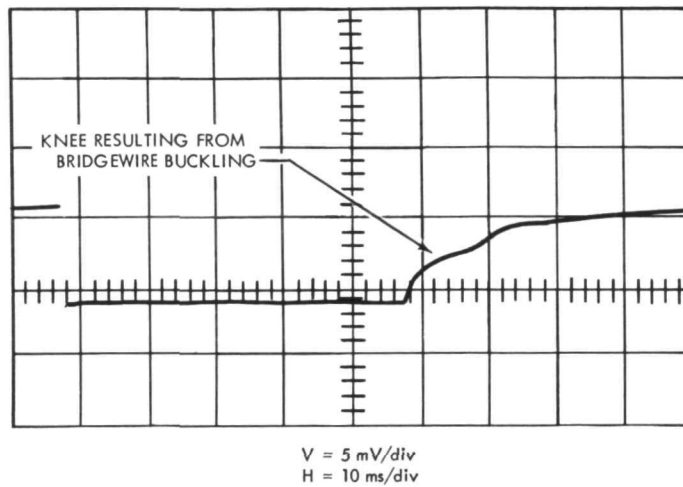


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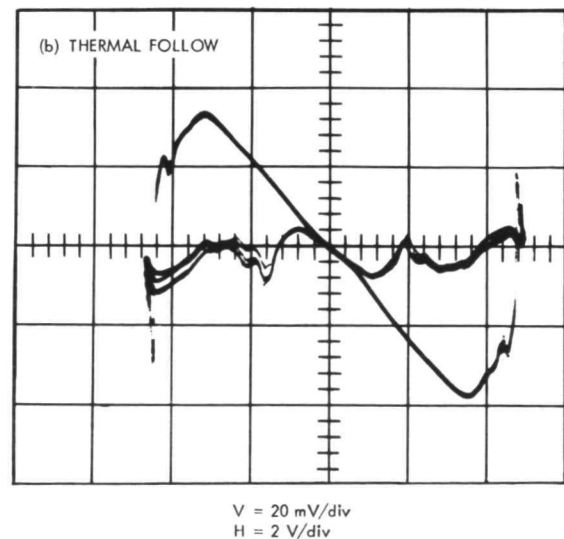
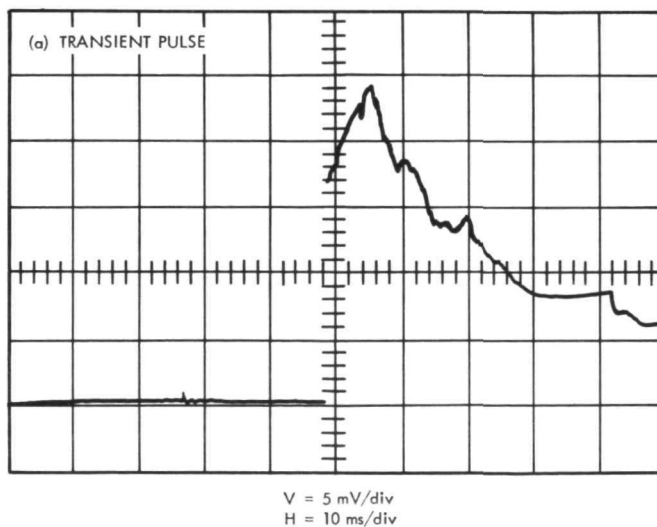
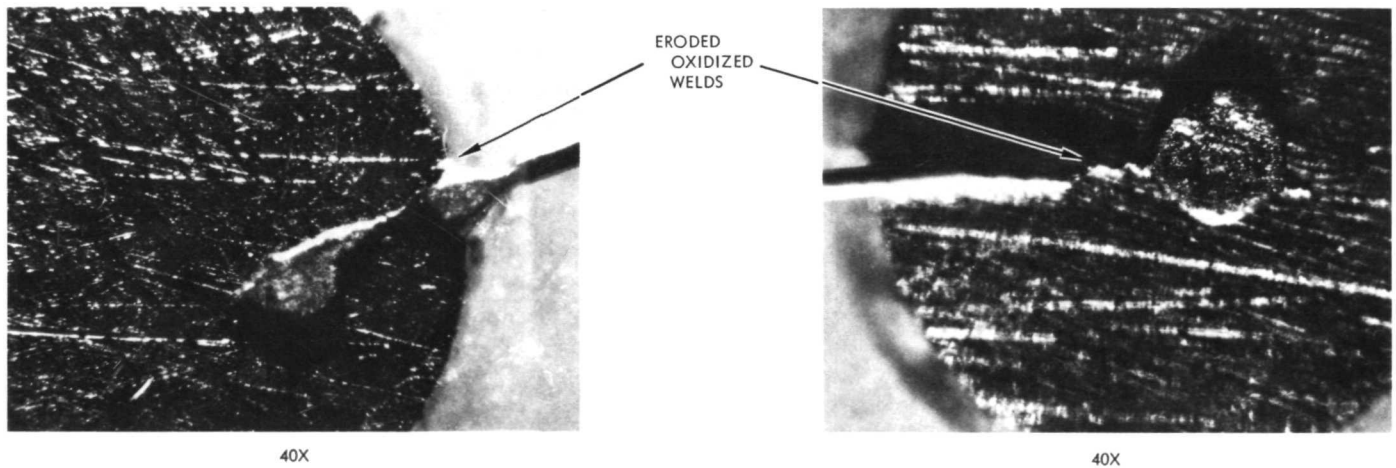
**Fig. 7. Photomicrograph (double exposure) of a bridgewire heating cycle in air, showing buckling of wire as temperature rises**



**Fig. 8. Tunneling effect resulting from bridgewire buckling**

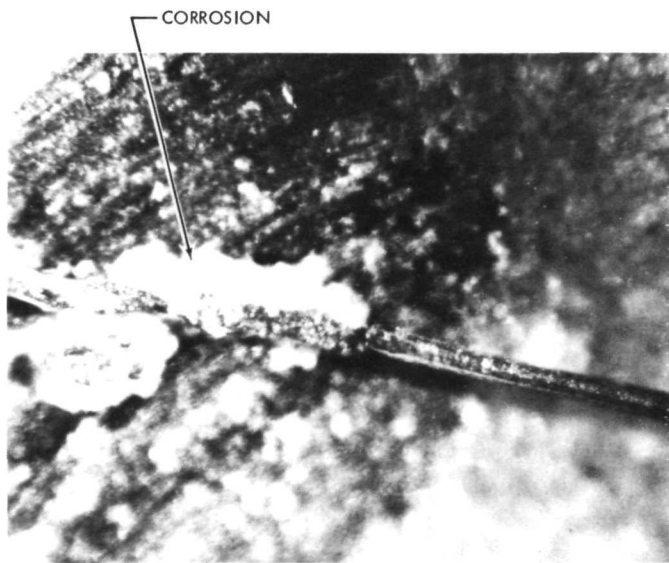


**Fig. 9. Heating curve resulting from poor contact between bridewire and explosive**

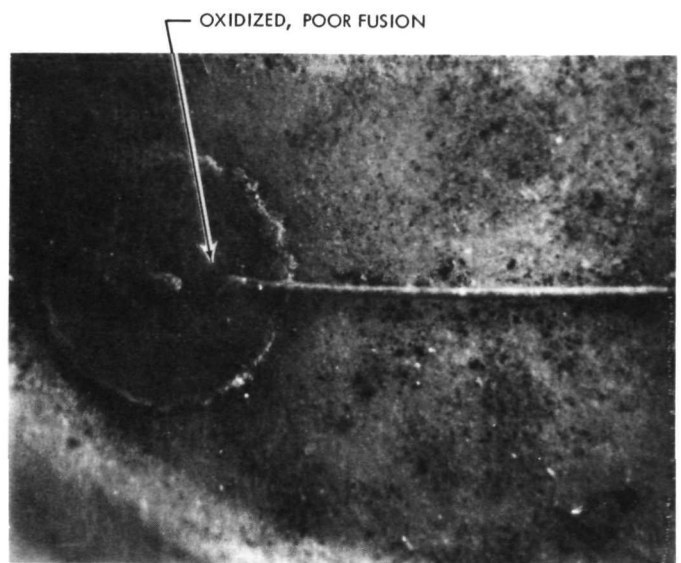


**Fig. 10. Heating curves resulting from photographed defective welds**





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**Fig. 11. Bridgewire welds of dissected EEDs that demonstrate nonohmic, nonlinear responses to transient pulse and thermal follow tests**

In a similar case, an EED displayed highly irregular and unstable heating curves indicative of poor bridgewire welding (see Figs. 12a and 12b). The EED was carefully dissected, leaving only the bridgewire/header/explosive interface intact. The explosive material on the bridgewire was found to be at a low density, slightly above bulk density. The EED was then subjected to the transient pulse test, with the exception that the driving voltage was increased so as to heat the wire above the normal operating test temperature but not high enough to cause initiation. The pulsing at this level would stress the bridgewire beyond the stress experienced in a normal test. The pulsing was continuous for the purpose of accelerating any weld defects to the point of failure.

One would not normally use the transient pulse test in this manner when making a nondestructive measurement. However, for this application the equipment became an appropriate tool to study the suspected fault. After approximately 15 min of pulsing, the bridgewire circuit opened without causing ignition of the pyrotechnic material. The explosive material was removed from the bridgewire and header surface, and the bridgewire circuit was examined. One end of the bridgewire had separated from the post, causing the open circuit.

From the appearance of the weld (see Fig. 12c), it was obvious that the bridgewire was poorly fused to the post. The other end of the bridgewire was more firmly at-

tached to the post but not in a proper manner. The failure of this device is attributed to the poor bridgewire welds which were detected by the nondestructive tests. Although the EED was driven to failure by pulsing the bridgewire with the transient pulse equipment, the same result could have occurred from thermal cycling.

Another area of considerable interest sensed by the transient pulse technique was the identification of phase changes taking place within the explosive mixture. Figure 13 shows two EEDs which exhibited abnormal responses. The heating curve climbs to a peak temperature and then falls off, suggesting that cooling of the bridgewire is taking place.

It was known that the explosive mixture pressed on the bridgewire contained a 5% Viton® binder. It was further learned that Viton binders for EED applications are usually dissolved in acetone or methyl ethyl ketone (MEK) and wet-mixed with the explosive materials. The mixtures are then oven-dried to drive off the solvent.

In practice, driving out all of the solvent from Viton by heating is quite difficult (Ref. 5). It is believed that the abnormal heating curves of Fig. 13 were a result of trapped acetone or MEK in the Viton which, upon heating of the bridgewire, changed the solvent from a liquid to a gaseous phase, accounting for the cooling observed. Dissection of the faulty EEDs revealed that the Viton

had formed a thin skin (approximately 2.48 mm (15 mils) thick) about the inner walls of the ceramic cup and surface of the header. This may have occurred because the trapped solvent kept the Viton very plastic and when the explosive mixture was pressed into the ceramic cup the pressure allowed the Viton to exude to the inner surfaces.

Figure 14 shows photomicrographs of the explosive mixture removed from EEDs, emphasizing the exuded Viton. The examination showed that the explosive mixture was not homogeneous and that the bridgewire was not in intimate contact with the reactive ingredients of the explosive mixture. The implication of such conditions are obvious and they should certainly be avoided.

To further substantiate that the transient pulse technique was detecting a phase change, heating curves were obtained for Viton, acetone, MEK, and a mixture (50/50) of acetone and Viton. Figure 15 shows these heating curves. Viton exhibits a normal heating curve, while acetone, MEK, and acetone/Viton (50/50) definitely exhibit a phase change at bridgewire temperatures normally attained in the test.

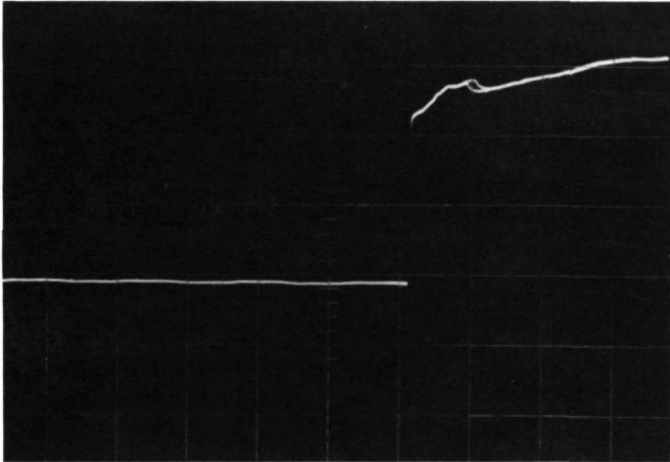
It was stated earlier that the transient pulse technique allowed for the calculation of thermal conductance, thermal time constant, and cold bridgewire resistance. These parameters can be beneficial in further narrowing the sample selected for use. Recently a study was made of a single bridgewire EED supplied by the Manned Space Center, Houston, Texas. Two samples (50 each) each manufactured by different companies, were subjected to the transient pulse and electrothermal follow techniques. It was found that both samples displayed

equivalent heating curves, and no abnormalities were observed. One could stop at this point and randomly select units from either sample. However, on the basis of one or more of the thermal parameters, i.e., the thermal time constant, the distribution could be reviewed and the sample further narrowed by selecting units within a chosen bandwidth.

## V. Conclusions

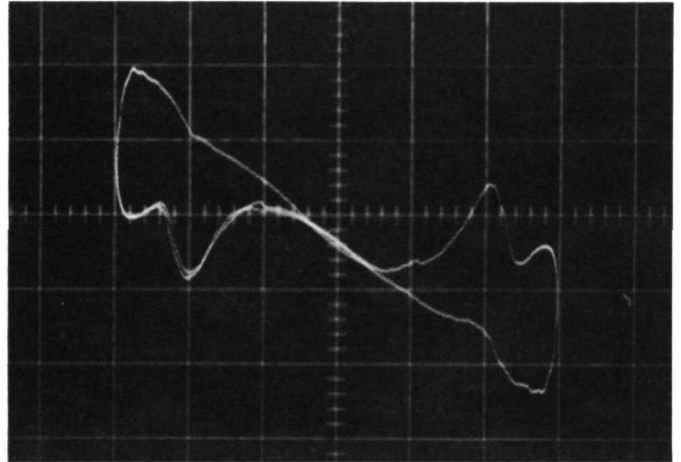
A number of faults have been detected and the causes determined by the transient pulse and electrothermal follow techniques. Not all faults have been detected but it is felt that those discussed in this paper are most likely to lead to failure. Different EED designs will generate variations of the responses discussed. The basic abnormalities have been discussed; any deviations from these must be attributed to the design of the EED under study. For those who must demonstrate very high reliabilities and confidences, these techniques will provide a means to minimize the number of EEDs that must be destructively tested. Total normality can be obtained by culling out abnormal or suspicious units (Ref. 6). These techniques can be conveniently applied to in-process quality control. Specifically, the transient pulse can be a total inspection and acceptance tool. In addition, designers of EEDs will find the techniques useful in optimizing their designs and detecting hidden and subtle potential faults.

The Jet Propulsion Laboratory has applied these techniques in the evaluation of EEDs for the Mariner 9 spacecraft and intends to use them for future EED evaluations.



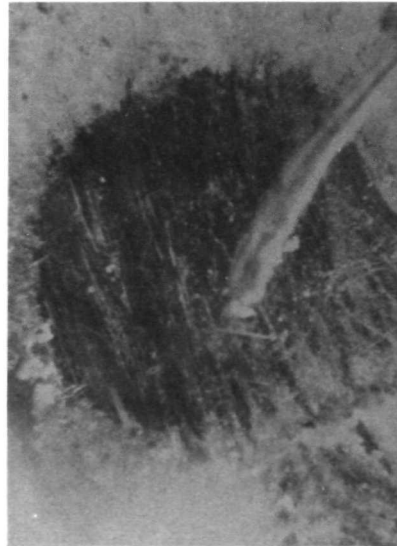
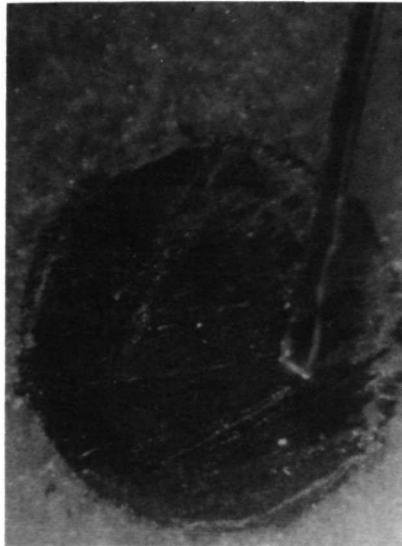
(a) TRANSIENT PULSE RESPONSE

V = 5 mV/div  
H = 10 ms/div



(b) ELECTROTHERMAL FOLLOW RESPONSE

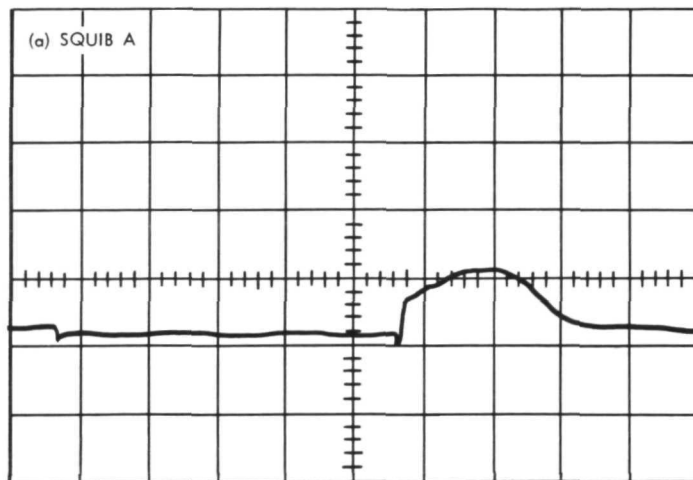
V = 20 mV/div  
H = 2 V/div



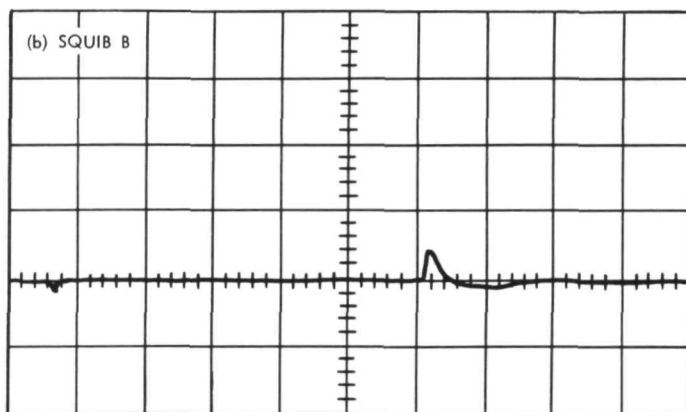
(c) PHOTOMICROGRAPHS OF BRIDGEWIRE AND POSTS

**Fig. 12. Heating curves and weldments for an EED with defective bridgewire welds**





V = 5 mV/div  
H = 10 ms/div

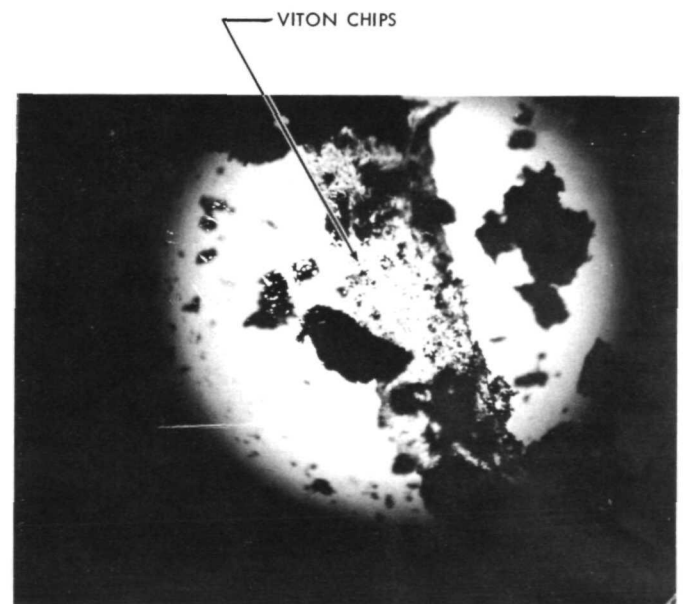


V = 5 mV/div  
H = 10 ms/div

**Fig. 13. Heating curves resulting from an apparent phase change taking place within the explosive mixture**

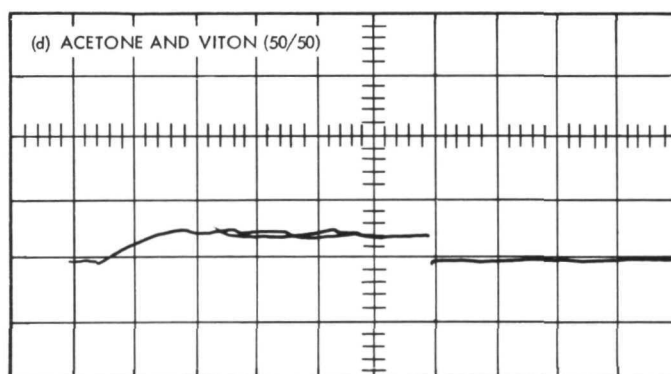
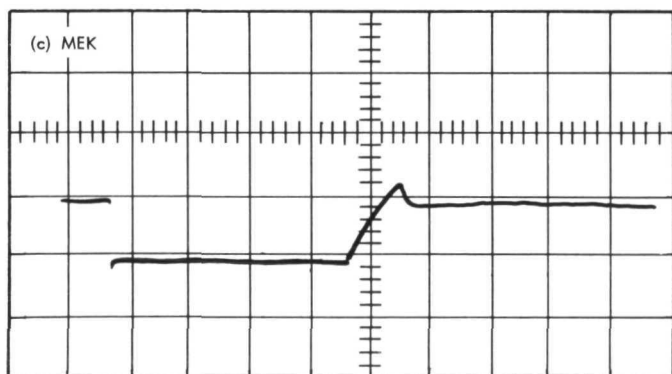
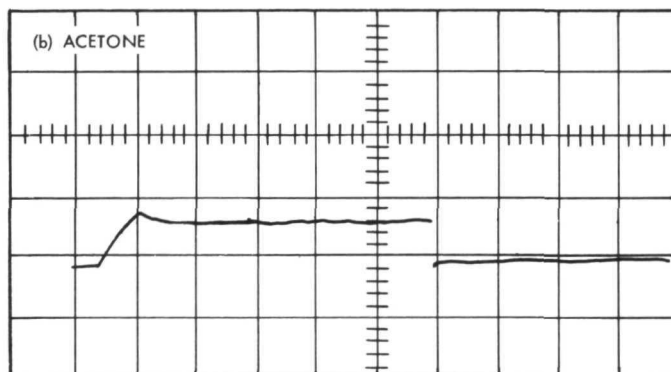
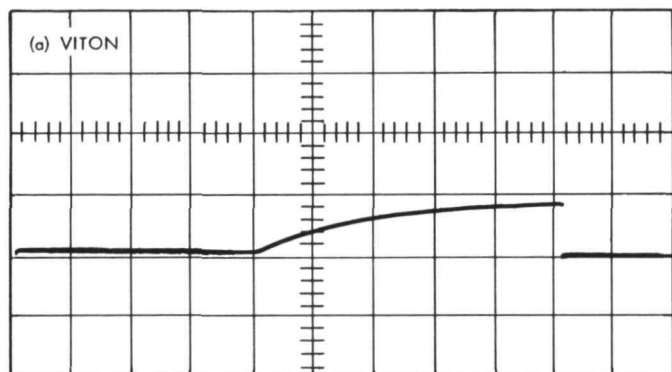


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**Fig. 14. Photomicrographs of exuded Viton in explosive mixture after dissection**



V = 5 mV/div  
H = 10 ms/div

Fig. 15. Heating curves for various bridgewire environments

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